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Geological Characterisation of the Otway Project Pilot Site: What a Difference a Well Makes.

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Abstract

This paper summarises the modelling approach and lessons learnt at the CO2CRC Otway Project Pilot Site and how uncertainties were significantly reduced by utilising a new CO_2 injection well for multi-disciplinary formation evaluation. From subsequent data analysis porosity/permeability relationships were better constrained by a depositional facies model. With a better informed geological model, the dynamic simulation results produced an excellent history match with pre and post production data from the depleted gas field. Further more, prediction of the CO_2 plume direction and shape, and arrival times of the CO_2 at the monitoring well, may now be regarded with a higher degree of confidence.

Keywords: Site characterisation; geological storage; reservoir modelling; demonstration site.

1. Introduction

The largest demonstration project of geological CO_2 storage and monitoring in Australia is currently underway in a depleted gas field located in the onshore portion of the Otway Basin, Victoria (figure 1). Prior to injection, it was necessary to fully characterise the target reservoir and overlying formations to properly risk manage the project and guide the basis of design for a comprehensive monitoring program.

At the foundation of such reservoir characterisation is the static three dimensional (3D) geological model which incorporates geological details such as porosity, permeability, pressure, and the geometry of the reservoir including faults, sedimentary layers, and facies distribution, as these are the primary characteristics controlling the behaviour of stored carbon dioxide (CO_2) (Bachu. Uncertainty associated with this modelling, especially in the case where

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data are scarce, must be captured by multiple models in order to cover all plausible geological scenarios including, for example, modelling extreme cases to define minimum and maximum migration times. However, should new high quality data become available, the number and range of geological models may be narrowed down to produce a single "base case". This is just what happened at the Otway Project when the new CRC-1 well was drilled in the beginning of March 2007. New insights into the reservoir geology and quality were gained through an extensive coring and logging program. Geophysical data provided increased confidence in the seismic interpretation and depth modelling. As a result regulators could make a better informed assessment of risks, suitability of the monitoring program, and finally assurances about the long term fate of the injected CO_2 once the project concludes.

The case study presented herewith provides an example of methodology for storage site chracterisation and modelling which may be employed at similar large scale demonstration or commercial storage sites

2. The CO2CRC Otway Project

The Naylor Field was selected for the pilot site because it is a depleted natural gas field with available well, production, and 3D seismic data, and is close to a nearby CO_2 source (the Buttress field). The storage target is a small (6 BSCF of OGIP), fault bound structure within the late cretaceous Waarre C Formation, sealed by the overlying Belfast Mudstone. The aim of the Otway Basin Pilot Project (OBPP) is to demonstrate that CO_2 can be effectively captured, transported, stored and monitored underground under Australian conditions (Sharma *et al.,* 2006). CO_2-rich gas (80% CO_2; 20% methane) is extracted from the Buttress-1 well. It is then compressed and transported via an underground, 2.25 km long, stainless steel pipeline. Over two years, up to 100,000 tonnes of the CO_2-rich gas stream will be injected at supercritical state into the depleted gas reservoir at a depth of 2050mSS via the CRC-1 well. The plume migrates up-dip under buoyancy beneath the Belfast Mudstone and Flaxmans Formation seal. A comprehensive monitoring and verification plan is in place to track the plume and test the validity of various techniques during injection and with an extended observation period continuing post injection in surface, sub-surface, and atmospheric domains.

With these objectives in mind, there were several critical factors to consider in order to place the injection well in an optimal location, down dip from the monitoring well. In order to optomise seismic delectability it was desirable to locate injection far enough away from the current remaining gas cap at the top of the structure. Conversely, in order to achieve the extensive geochemical down-hole sampling at Naylor-1, it was necessary to locate the injector close enough to have breakthrough of the plume within the project time frame.

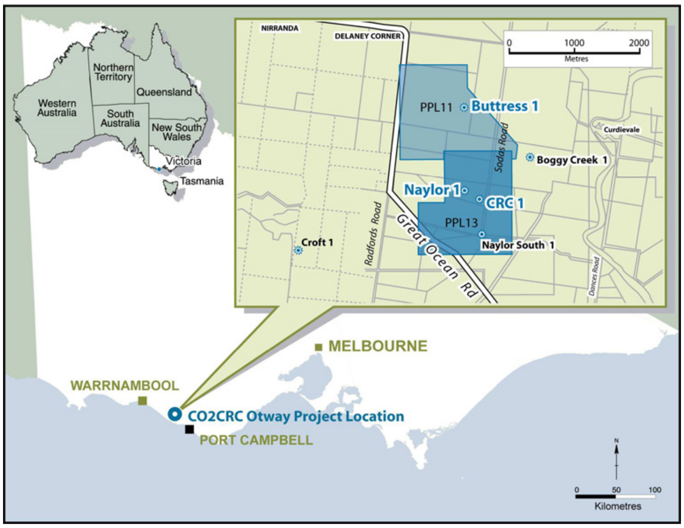

Figure1: location of the Otway Project, petroleum lease tenements, and key wells including the CRC-1 injector.

3. Uncertainty Risking

Central to the decision making process was the geological modeling and dynamic simulations which focused on objectives of: time to breakthrough at the Naylor-1 well (a target of between 6 and 12 months was set); addressing the risk in the inherent uncertainty of reservoir heterogeneity; and modelling the likely flow behavior of any injected CO_2 (Spencer *et. al*., 2006). At the time, data paucity was an issue. Naylor-1 was completed as an 88.9mm (3½ inch) cased mono-bore with only a basic wire-line log suite. There was no conventional core, SWC, or biostratigraphy in this, or the nearby Naylor South-1 well. Although there was good seismic resolution over the area, well control on the velocities and depth conversion relied on extrapolation of time-to-depth relationships from nearby wells. Furthermore, seismic stratigraphy interpretation was of limited value as the reservoir is thin (25-30m) and deep (1.5-1.6 seconds TWT), with residual gas effects and therefore occurs at or below the limit of separability. Reservoir properties (depositional facies, porosity, permeability) were characterized from regional data adding to the complexity and uncertainty of the assessment.

For the purpose of proper due diligence, modeling identified and investigated the impact of three key uncertainties:

1. Structural: architecture and dip of the reservoir.
2. Stratigraphic: paeleo depositional model
3. Reservoir quality: porosity and permeability

The recommended approach was to construct multiple cases each with several realizations using different averaging techniques e.g. deterministic, object and stochastic, the result is four different key-case geo-models that cover the full range of possible scenarios (table 1).

	Case	Description	Interpretation
1	Fastest Migration Rate	High permeability, few shale baffles, maximum dip.	Optimistic, but geologically unlikely
2	Transgressive Shoreline Model	Regional depositional model with large marine shale bodies orientated east-west acting as barriers to CO_2 flow.	Considered geologically possible at the time
3	Regressive Braided Fluvial Model	High net-to-gross cross-bedded sandstone reservoir with minor shale baffles orientated roughly in the direction of structure.	Geologically most likely.
4	Slowest Migration Rate	Low permeability, low connectivity, gentle dip.	Pessimistic, geologically unlikely.

Table 1: Summary of pre-CRC-1 geo-model cases.

This was essentially a probabilistic approach with moderate to high uncertainty, but was able to provide high and low flow case extremes. Dynamic simulation investigated sensitivity to variables in addition to those geological factors listed above, such as permeability, Kv/Kh ratios, relative permeability; and finally well location in relation to the monitoring bore and structural dip (Xu .et al., 2006). History matching to production data revealed little agreement with cases 1 and 2 so these were discounted, but a good match to cases 2 and 3 was found. Results for break through in case 2 and 3 were mainly impacted by the distribution and size of shale baffles (times ranged from 6-14 months).

Recent advances in the understanding of the depositional environment of the Waarre C formation (Sharp and Wood, 2004, and Faulkner, 2000) point to case 3 as the most geologically likely scenario, however, it was recommended that the new well should provide core to firm up conclusions on the depositional model.

4. New Insights

CRC-1 was spudded on February 15th, 2007 and reached total depth of 2249mRT, 109 metres into the Eumeralla formation, on the 8th of March, 2007. It was set and cased as a 4½ inch vertical mono bore. The suite of wire-line log information gathered comprised Gamma Ray, Nuclear Mangetic Resonance (CMR), Elemental Capture Spectroscopy (ECS) and Formation Micro Imager (FMI) which were recorded to complement the standard resistivity-density-porosity logs. In addition were several MDT tests, and 49m of recovered core -24m of continuous core through the Waarre-C Formation. Core analysis included Computed Tomography (X-Ray CT scanning), Gamma Ray, mini profile permeability, conventional porosity/permeability plug analysis, and SCAL tests (CO_2 core flooding experiments). In addition there were new data acquired in Naylor-1 prior to the installation of the down hole monitoring assembly that included wire-line logs and Vertical Seismic Profiling (VSP) contributing to an improved database for further reservoir characterisation and modelling (table 2).

Previous Database	Updated Database
No full hole cores or SWCs therefore; • no palynological or reservoir analyses available.	**49 m of core, 24m through the Waarre C reservoir:** • Conventional and special core analysis provided quantitative data on porosity/permeability. • Core logging improved facies model.
Minimum wire-line log suites therefore; • only basic petrophysics: porosity and water saturation.	**Newly aquired Nalyor-1 and CRC-1 Petrophysical logs, MDT, and injection tests:** • Petrophysical interpretation and fluid saturations incorporated in model.
No VSP therefore; • poorer understanding of velocity gradient.	**New Naylor-1 and CRC-1 VSP data**: • Full Earth velocity model constructed. • Confirm current depth conversion model.
No GWC in Naylor-1 well and no local water gradient; • Simulation models less constrained. • Reserves estimation imprecise.	**Naylor-1/CRC-1 wire-line logs and hydrodynamic data:** • Reduced uncertainty in the post-production GWC. • Improved dynamic modeling history matching.

Table 2: Comparison of databases used in pre and post CRC-1 geo-models.

4.1. Sedimentology

Before the core was unwrapped, high resolution X-Ray CT scanning was performed to preserve a record of the internal features. Few fractures were noted, but fine lamina in the form of thin carbonaceous layers was recorded throughout. Total Core Gamma Ray allowed for accurate placement of the cored section against well log down-hole depths. The core was then slabbed and a detailed description and photographs were made of the clean surface. Sedimentological observations of the cores showed complex stratigraphy that included presence of incised valley fill deposits within the Waarre C Formation, overlain by transgressive to offshore open marine deposits in the Flaxman Formation (Dance and Vakarelov, 2008). These two units appear to be separated by a weak unconformity sequence boundary. This supports new biostratigraphic evidence that the two formations are not contemporaneous (Partridge, 2005) thus further discounting the transgressive marine depositional model (case 2).

Six depositional facies were identified (figure 2). The distinct sedimentary structures such as intense bioturbation, wavey mud drapes, and rhythmic cylces of stacked rippels suggest tidal influence in a near marine setting. This accounts for the presence of marine biota in the biostratigraphic analysis, and moves away from the entirely braided fluvial depositional model (case 3).

Deposition of the Waarre C Formation was likely affected by synchronous structural control, which had an important influence over position of feeder systems and valley incision. The stacked nature of incised valleys interpreted from core observations can be related to river courses forced to conform to topographic troughs related to underlying tectonic and structural control.

4.2. Formation evaluation

Porosity and Permeability measurements were performed on vertical and horizontal core plugs at in-situ stress conditions, and supplemented by Profile Permeametry measurements recorded on the whole core surface every 5 to 10cms. Once the down-hole depths from the 47 core measurements were corrected (using core and down-hole GR correlation), the core porosity and permeability were matched to the log curves. The core derived Bulk Density was compared with the LOG derived bulk density and the match was found to be satisfactory. During the petrophysical modeling two permeability logs were derived of Low and High resolution from the CMR-DMR logs. The Low resolution log showed little agreement with the permeability measurements from the core, where as the match was good for the high resolution logs. This highlights the need for high resolution logs to match with cores for accurate calibration of down-hole data.

Reservoir quality appears to be related with the depositional facies (figure 2). For example, the tidal reworked facies has the highest permeability thought to be due to the constant reworking of the sediment during deposition. The conglomeritic facies has poorer quality due to the poor sorting, angular grains. Petrographic descriptions and scanning electron microscopy (SEM) was used to identify the presence of Kaolinite clays which occlude the pore spaces in this facies as a result of altered plagioclase grains and lithics.

Injectivity testing, using water, provided information for the bulk permeability of the reservoir. Initially injectivity was poor and pressure built up rapidly down hole. This was assessed as being due to formation invasion of the drill fluids and mud build-up on the surface of the high permeability reservoir sands. The reservoir was allowed to back flow into the well, and the tests were performed again with excellent results. This confirms the high permeability (1-5 Darcy) recorded in conventional core analysis of some of the sands.

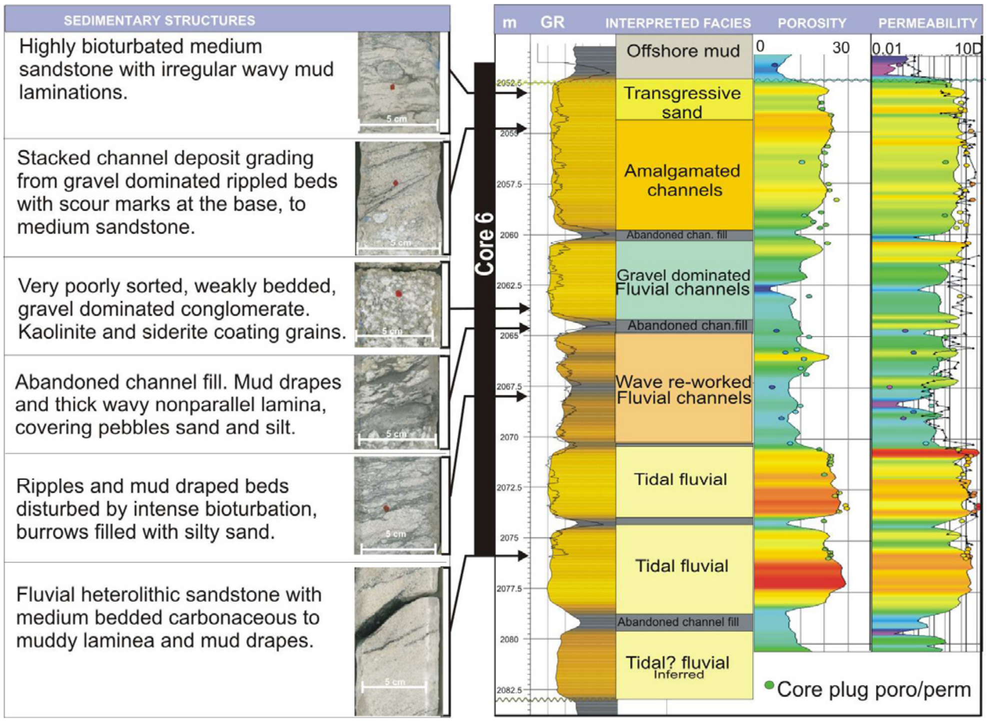

Figure 2: CRC-1 core photographs and descriptions compared to the well composite. Left to right core GR matched over the down-hole GR log, interpreted facies, core porosity measurements over the Phi log, core permeability-Klinkenberg corrected and mini-perm profile (black triangles) showing good agreement with down-hole permeability log.

4.3. Base Case Static Model

A new facies based model was created with flow properties as observed at the core, down-hole and reservoir scale (figure 3). Porosity permeability relationships were honored away from the wells using principals of the depositional facies distribution. Analogues and conceptual models guided ranges of the expected length and width of facies bodies. For example the abandoned channel fill shale baffles were not expected to exceed more than 80m wide and 100m long due to the repeated channel incision. Geophysical mapping (acoustic impedance) and dip meter data were used to help guide anisotropy of the channel bodies which were approximately in a north-west to south-east orientation. Dynamic simulations were performed and provided a good history match with pre and post production data. Furthermore, the breakthrough times were predicted within a narrower margin of between 6 and 9 months.

CO_2 injection began at the pilot site in April, 2008. During the geochemical acquisition run on the 11th of September, 2008, a U-Tube in Nalyor-1 changed from previously sampling formation water to sampling largely gas, which had a CO_2 content of almost 50%. While analysis is ongoing, the behavior of the system is within the model predictions, adding confidence to the modeling simulations constructed prior to injection.

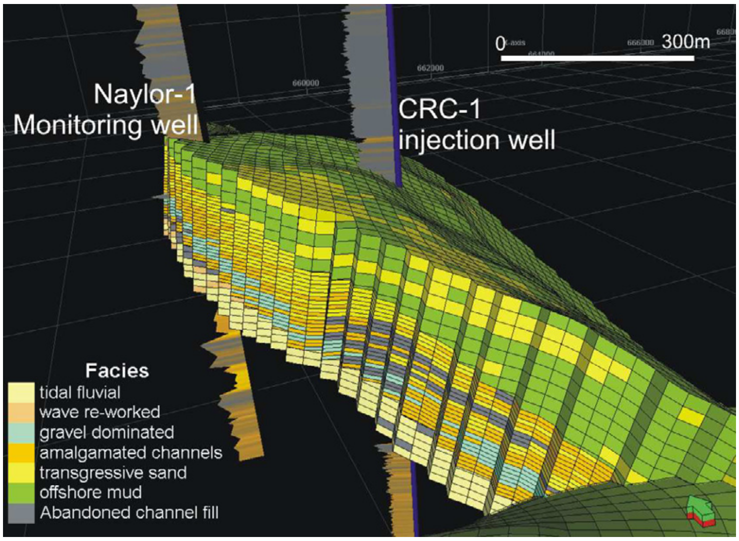

Figure 3 base case facies model distribution of the Waarre C and overlying Flaxman Formation.

5. Conclusions

Key data acquisition technologies were used for this CO_2 Sequestration project which helped in minimizing the uncertainties in the subsurface characterization. The Waarre C formation has excellent reservoir quality with high porosity sands and multi Darcy permeability. A comprehensive coring program provided information needed to improve the facies definition and porosity/permeability relationships within the geo-models and consequently improve the reliability of the simulation results. The reservoir is comprised of six different facies units each with distinct porosity and permeability relationships, as well as different vertical (K_v) to horizontal (Kh) ratios and lateral anisotropy (K x/y). Gravel dominated channels have variable porosity and permeability due to poor sorting and clay development in this relatively immature sediment. The wave reworked facies is comprised of finely laminated silts and shales reducing vertical permeability. The highest permeability measurements were recorded in the tidal fluvial, amalgamated channel deposits and transgressive marine sands.

The multiple case static modeling was necessary in the early stages of the project to minimize risk, however the detailed base case model resulted in improved history matching for the dynamic simulation and provided a smaller range of possibilities for expected break through at the monitoring well.

This research has demonstrated the need for targeting data acquisition programs to reduce uncertainty. Costs and time limitations associated with any acquisition program will of course have to be considered and it may follow that at some sites, uncertainty surrounding reservoir characterization will be negligible to the project's success. For example, regionally derived permeability information may be sufficient to characterize a relatively homogeneous reservoir, and there will be less of a need for expensive core analysis. Other sites may be considered higher risk and as such require greater detailed work.

6. Acknowledgments

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